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(54) Title: PHASE CONTRAST IMAGING
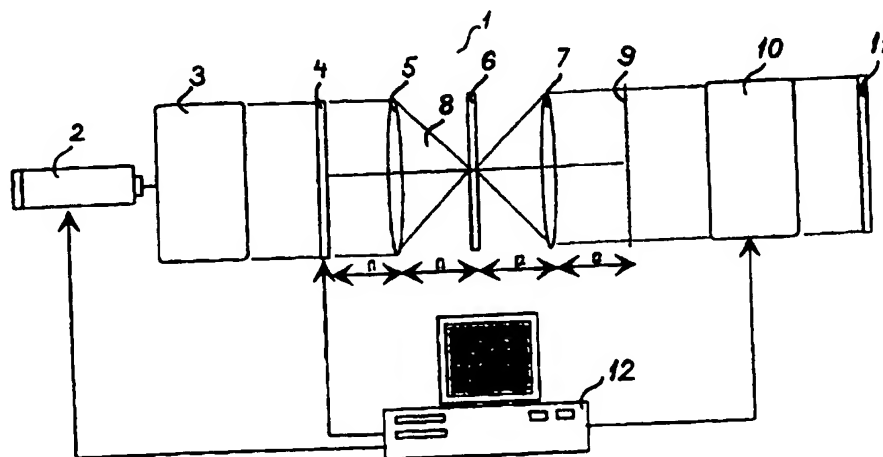
(57) Abstract

The invention relates to a method and a system for synthesizing a prescribed intensity pattern based on phase contrast imaging that is not based on the assumption of prior art methods that the pahase shift ϕ is less than 1 radian. An improved method based on a simple imaging operation with a simple one-to-one mapping between resolution elements of a spatial phase modulator and resolution elements of the generated intensity pattern is provided. According to the invention a method is provided for synthesizing an intensity pattern with low loss of electromagnetic energy. comprising spatial modulation of electromagnetic radiation with a spatial phase mask for modulation of the phase of the incident eletromagnetic radiation by phasor values of individual resolution elements of the spatial phase mask. each phasor value being determined in such a way that the values of the Fourier transformed phasors attain predetermined values for predetermined spatial frequencies. and the phasor value of the specific resolution element of the spatial phase mask corresponds to a distinct intensity level of the image of the resolution element in the intensity pattern. and a spatial phase filter for phase shifting of a part of the electromagnetic radiation. in combination with an imaging system for generation of the intensity pattern by interference in the image plane of the imaging system between the part of the electromagnetic raidation that has been phase shifted by the phase filter and the remaining part of the electromagnetic radiation.

Phase Contrast Imaging

FIELD OF THE INVENTION

The invention relates to a method and a system for synthesiz-
ing a prescribed intensity pattern based on phase contrast
imaging.

5 BACKGROUND OF THE INVENTION

It is well known to form an image on an illuminated surface
of a body by absorption or blocking of energy of an illumi-
nating beam. For example in an overhead projector, an over-
head transparent absorbs or blocks part of the light beam of
10 the projector whereby a large image of an overhead is formed
on a screen. However, this results in a loss of light inten-
sity as part of the emitted light from an image forming
system is reflected or absorbed.

To avoid loss of energy causing, e.g. loss of light intensity
15 of the synthesized intensity pattern, power dissipation
generating heat in components of the system, etc., methods
and systems have been developed wherein the phase of a light
beam is modulated instead of the amplitude or intensity of
the light beam, as modulation of the phase of the light beam
20 do not lead to loss of energy. The phase modulation is fol-
lowed by a conversion of the phase modulation into an ampli-
tude or intensity modulation.

A diffractive optical element, such as a holographic optical
element, may be used to generate a phase modulation. Then,
25 the resulting intensity modulation at each point of a picture
formed by conversion of the phase modulation into intensity
modulation will depend upon the phase modulation values at
each point of the diffractive optical element as the light
intensity at each point of the picture is formed by a coher-
30 ent superposition of light received from the entire surface
of the diffractive optical element. Diffractive optical
elements are rather complex to design for synthesis of a
prescribed intensity pattern.

Imaging methods and systems may also be used in connection with phase modulation. These methods and systems are charac- terized by the fact that the intensity of a point of a pic- ture formed by conversion of phase modulation into intensity
5   modulation will depend upon the phase modulation value of one point of the phase modulator only as this point is imaged onto the picture point in question by the imaging system. This one-to-one relationship makes the design of phase modu- lators in these systems simple. Methods and systems of this
10 kind are named phase contrast imaging methods and systems.

Phase contrast imaging methods were originally developed within the field of microscopy. Many objects of interest in microscopy are largely transparent, thus absorbing little or no light. When light passes through such an object, the
15 predominant effect is the generation of a spatially varying phase shift which can not be seen by a human as the eye of a human responds to light intensity and colour and does not respond to the phase of light.

In 1935, Fritz Zernik proposed a phase contrast technique
20 which rests on spatial-filtering principles and has the advantage that the observed intensity is linearly related to the phase shift introduced by the object.

Suppose that a transparent object with amplitude transmittance

$$t(x,y) = \exp[j\phi(x,y)] \tag{1}$$

25

is coherently illuminated in an image-forming system. For simplicity, a magnification of unity is assumed and the finite extent of the exit and entrance pupils of the system is neglected. Further, a necessary condition to achieve
30 linearity between phase shift and intensity is that the phase shift ϕ be less than 1 radian, in which case the amplitude transmittance can be approximated by

$$t(x,y) = 1 + j\phi(x,y) \qquad (2)$$

The terms of order ϕ^2 and higher are neglected in this approximation. It is seen that the first term of (2) leads to a strong wave component that passes through the sample without change, while the second term generates weaker diffracted light that is deflected away from the axis of the system.

The image produced by a conventional microscope can be written

$$I \sim |1 + j\phi|^2 \sim 1 \qquad (3)$$

where the term ϕ^2 has been approximated by zero. It is seen that the diffracted light is not observable because it is in phase quadrature with the strong background. As Zernik recognized that the background is brought to a focus on-axis in the focal plane while the diffracted light - containing higher spatial frequencies - is spread away from the focal point, he proposed that a phase-changing plate be inserted in the focal plane to modify the phase relation between focused and diffracted light.

The phase-changing plate can consist of a glass substrate on which a small transparent dielectric dot has been coated. The dot is placed at the center of the focal plane and has a thickness and index of refraction such that it retards the phase of the focused light by either $\pi/2$ radians or $3\pi/2$ radians relative to the phase retardation of the diffracted light. In the former case the intensity in the image plane becomes

$$I = |\exp[j(\pi/2)+j\phi|^2 = |j(1+\phi)|^2 \sim 1 + 2\phi \qquad (4)$$

while in the latter case

$$I = |\exp[j(3\pi/2)+j\phi|^2 = |j(-1+\phi)|^2 \sim 1 - 2\phi \qquad (5)$$

Thus, the image intensity has become linearly related to the phase shift ϕ. When the phase of the background is retarded by $\pi/2$, the result is known as positive phase contrast, while a $3\pi/2$ retardation is said to yield negative phase contrast.

5   It is seen that the method described above leads to a phase contrast imaging method that provides a small phase signal that is superimposed on a large DC-component. This leads to an important disadvantage of the method because, typically, it will be necessary to attenuate the DC-component to enhance
10 the information contained in the phase modulated signal. However, the attenuation of the DC-component leads to loss of energy. This kind of filtering is usually denoted Dark Field Filtering.

It is another disadvantage of the phase contrast imaging
15 method described above that it is based on the assumption that the phase shift ϕ is less than 1 radian which is very often not fulfilled in practical real-life applications. However, the theory is still applied to such applications, disregarding the fact that the basic assumption is not ful-
20 filled, and this leads to non-optimized technical solutions.

In EP 0 657 760 a phase contrast imaging system is disclosed in which an image simulation and projection system is based on the Texas Instrument flexure beam digital mirror device (DMD). The flexure beam DMD is used for analog phase
25 modulation of reflected light and the phase modulation is converted to amplitude modulation utilizing a phase contrast imaging method. The flexure beam DMD provides a flicker-free modulated wave and accordingly, optical image sensor synchronization is not needed. The system disclosed operates
30 according to the Zernike method and, thus, includes the corresponding disadvantages described above.

Another example of a phase contrast imaging system is disclosed in GB 2 199 716, wherein an optical guide-beam projector for a missile guidance system is disclosed that

provides a spatially intensity modulated guide-beam. A spatial phase modulator is used to generate the guide-beam. The phase encoding of the spatial phase modulator constitutes a periodic square-wave modulation (50% duty cycle) of two phase

5 values 0 and $\pi/2$. The phase modulation is converted into an amplitude modulation by Fourier transforming lenses and a phase plate providing a phase shift of the background signal by $\pi/2$. A method for synthesizing the specific intensity pattern of the optical guide-beam based on phase contrast

10 imaging is not disclosed in this document.

A similar example of a phase contrast imaging system is disclosed in "Array illuminator based on phase contrast", Applied Optics Vol. 27, No. 14, pp. 2915-2921 (1988). A method is disclosed of converting a wide beam of uniform

15 intensity into an array of bright spots without losses. The input spatial phase mask constitutes a periodic array of phase dots with the phase value π, the remaining area of the phase mask having the phase value 0. The phase modulation is converted into an amplitude modulation by Fourier

20 transforming lenses and a phase plate providing a phase shift of the background signal by π. The method is limited to the implementation of periodic array configurations with the binary phase values 0 and π.

It is well-known to use so-called "radiation focusators",
25 i.e. computer generated holographic optical elements, for spatial phase modulation of a light beam, e.g as disclosed in Special Issue on Computer Optics in the USSR, Optics and Lasers in Engineering, Vol. 15, no. 5 1991. However, such elements are complicated to synthesize. Typically, they are

30 synthesized in such a way that the desired image is formed in the Fresnel region or the Frauenhofer region. Thus, the intensity of a resolution element in the generated image is a function of several, typically all, phase values of the resolution elements of the holographic optical element.

35 Obviously, this complicates the design of a general purpose holographic optical element and advanced, very time consuming

algorithms have to be applied. Further, the complicated design of the holographic optical elements renders it almost impossible to implement dynamically changeable spatial phase modulators with such elements.

5   It is a further disadvantage of holographic optical elements that a carrier frequency is needed to separate diffracted light from non-diffracted light resulting in an off-axis system geometry and a need for a diffractive medium that can support these high frequency terms.

10   SUMMARY OF THE INVENTION

It is an object of the present invention to provide an apparatus of the above kind which apparatus is robust, compact, simple to design and relatively cheap to manufacture.

It is another object of the present invention to provide an
15   improved method and apparatus for phase contrast imaging that take all terms of the Taylor's series:

$$t(x,y) = e^{i\phi(x,y)} = 1 + i\phi(x,y) - \frac{\phi(x,y)^2}{2!} - i\frac{\phi(x,y)^3}{3!} + \frac{\phi(x,y)^4}{4!} + \ldots \quad (6)$$

into account and, thus, is not based on the assumption that the phase shift ϕ is less than 1 radian. It is important to
20   note that each term of the Taylor's series contribute to the DC-value of the function $t(x,y)$. This fact is not recognized in the art as the DC-value has until now been believed to be represented by numeral 1 in equation (2).

It is still another object of the present invention to pro-
25   vide an improved method and apparatus for phase contrast imaging without the need of attenuating the DC-component of the signal to enhance the information contained in the phase modulated signal.

It is yet another object of the present invention to provide an improved method based on a simple imaging operation with a simple one-to-one mapping between resolution elements of a spatial phase modulator and resolution elements of the gener-
5 ated intensity pattern.

According to the invention a method is provided for syn-thesizing an intensity pattern with low loss of electromag-netic energy, comprising spatial modulation of electromag-netic radiation with a spatial phase mask for modulation of
10 the phase of the incident electromagnetic radiation by phasor values of individual resolution elements of the spatial phase mask, each phasor value being determined in such a way that

    1) the values of the Fourier transformed phasors attains
        predetermined values for predetermined spatial fre-
15   quencies, and

    2) the phasor value of a specific resolution element of
        the spatial phase mask corresponds to a distinct
        intensity level of the image of the resolution
        element in the intensity pattern,

20 and a spatial phase filter for phase shifting of a part of the electromagnetic radiation, in combination with an imaging system for generation of the intensity pattern by interfer-ence in the image plane of the imaging system between the part of the electromagnetic radiation that has been phase
25 shifted by the phase filter and the remaining part of the electromagnetic radiation.

Although, the present method is related to encoding of spa-tial phase masks in two spatial dimensions (planar encoding), the principles of the method may be utilized for phase encod-
30 ing in one to three spatial dimensions and/or in the temporal dimension.

The electromagnetic radiation may be of any frequency range of the electromagnetic spectrum, i.e. the gamma frequency range, the ultraviolet range, the visible range, the infrared range, the far infrared range, the X-ray range, the microwave range, the HF (high frequency) range, etc. The present method
5 is also applicable to particle radiation, such as electron radiation, neutron radiation, etc.

Preferably, the electromagnetic radiation is monochromatic or quasi-monochromatic so that the energy of the electromagnetic radiation is concentrated in a narrow frequency bandwidth. As
10 the intensity pattern is synthesized by interference of two electromagnetic waves emitted from a common source of elec- tromagnetic radiation but the phases of which have been changed differently, it is required that the frequency range of the emitted electromagnetic radiation is sufficiently
15 narrow to ensure that the two waves of electromagnetic radi- ation are coherent so that their superposition generates the desired intensity pattern. If the frequency range is too broad, the two waves will be incoherent and the phase infor- mation will be lost as superposition of non-coherent waves
20 results in a summation of the intensities of the two waves. It is required that the difference between individual delays of electromagnetic radiation to be superpositioned is less than the wavelength of the radiation. This is a relaxed requirement that allows the electromagnetic radiation to be
25 relatively broad-banded. For example in the visible range a Xe-lamp or a Hg-lamp can be used as a light source in a system according to the present invention with the advantage compared to a laser light source that the speckle noise is reduced. The requirements of the spatial coherence of the
30 electromagnetic radiation depend upon the space bandwith product of the corresponding system and how close the required system performance is to the theoretically obtain- able performance of the system.

Preferably, the electromagnetic radiation is generated by a coherent source of electromagnetic radiation, such as a laser, a maser, a phase-locked laser diode array, etc. However a high pressure arc lamp, such as a Hg lamp, a Xe lamp, etc, may also be used and even an incandescent lamp may be used as a source of electromagnetic radiation in a low performance system.

A spatial phase mask is a component that changes the phase of an electromagnetic wave incident upon it. The spatial phase mask may transmit or reflect the incident electromagnetic wave. Typically, the spatial phase mask is divided into a number of resolution elements each of which modulates the incident electromagnetic wave by changing its phase by a specific predetermined value. The predetermined values are assigned to each resolution element in different ways depending upon the technology applied in the component. For example in spatial light modulators, each resolution element may be addressed either optically or electrically. The electrical addressing technique resembles the addressing technique of solid-state memories in that each resolution element can be addressed through electronic circuitry to receive a control signal corresponding to the phase change to be generated by the addressed resolution element. The optical addressing technique addresses each resolution element by pointing a light beam on it, the intensity of the light beam corresponding to the phase change to be generated by the resolution element illuminated by the light beam.

Spatial phase masks may be realized utilizing fixed phase masks, devices comprising liquid crystals and being based on liquid crystal display technology, dynamic mirror devices, digital micromirror arrays, deformable mirror devices, membrane spatial light modulators, laser diode arrays (integrated light source and phase modulator), smart pixel arrays, etc.

A spatial phase filter is typically a fixed phase mask, such as an optically flat glass plate coated with a dielectric layer at specific positions of the glass plate. However, the spatial phase masks mentioned in the previous section may

5   also be used for spatial phase filters.

The imaging system maps the phase modulating resolution elements of the spatial phase mask on the target surface of the synthesized intensity pattern. It may comprise a 4f-lens configuration (two Fourier transforming lenses utilizing transmission of light or one Fourier transforming lens util-

10   izing reflection of light) or a single imaging lens. However, any optical imaging system providing a filtering plane for the spatial phase filter may be applied in a phase contrast imaging system.

15   In the method according to the present invention, the syn-thesized intensity pattern is generated by superposition of two electromagnetic waves in the image plane of the imaging system. The spatial phase mask changes the phase values of an electromagnetic wave incident upon it and the imaging system

20   directs the electromagnetic wave with changed phases reflected from or transmitted through the spatial phase mask towards the spatial phase filter. The phase filter phase shifts a part of the electromagnetic radiation and the imag-ing system is adapted to superimpose in the image plane the

25   phase shifted part of the electromagnetic radiation with the part of the electromagnetic radiation that is not phase shifted by the spatial phase filter.

According to a preferred embodiment of the invention, the spatial phase mask is positioned at the front focal plane of

30   a lens while the spatial phase filter is positioned in the back focal plane of the lens, whereby a first electromagnetic field at the phase mask is Fourier transformed by the lens into a second electromagnetic field at the phase filter. Thus, specific spatial frequencies of the first electromag-

35   netic field will be transmitted through the spatial phase

filter at specific positions of the phase filter. For instance, the energy of the electromagnetic radiation at zero frequency (DC) is transmitted through the phase filter at the intersecting point of the Fourier plane and the optical axis 5 of the lens also denoted the zero-order diffraction region.

It is presently preferred that the spatial phase filter is adapted to phase shift the DC-part of the electromagnetic radiation and to leave the remaining part of the electromag- netic radiation unchanged or, alternatively, to leave the DC- 10 part of the electromagnetic radiation unchanged and to phase shift the remaining part of the electromagnetic radiation. The last alternative is preferred when the energy level of the DC-part of the electromagnetic radiation is so high that the phase shifting part of the phase filter will be destroyed 15 by it. For example in laser cutting, the DC level of the laser beam can be so high that a phase shifting dot posi- tioned at the intersecting point of the DC part of the laser beam at the phase filter would evaporate. It is also possible to block the electromagnetic radiation (no transmittance) in 20 the zero-order diffraction region, however, the DC energy of the radiation is then lost.

Below, an expression of the intensity of the synthesized intensity pattern as a function of the phasor values $\phi(x,y)$ of the phase mask, when the DC-part of the electromagnetic 25 radiation is phase shifted, is deduced.

Electromagnetic radiation incident on the spatial phase mask can be described by a function $A(x,y)$, where $A(x,y)$ is a complex number (amplitude and phase) of the incident field on the point (x,y) of the spatial phase mask. At the point 30 (x,y), the spatial phase mask modulates the phase of the incident radiation with a value $\phi(x,y)$ so that the field after reflection by or transmission through the spatial phase mask may be described by the function $A(x,y) * e^{i\phi(x,y)}$, $e^{i\phi(x,y)}$ being the phasor value of the point (x,y) of the 35 spatial phase mask. As $A(x,y)$ preferably is a constant value

over the entire surface of the spatial phase mask, the term
is left out of the following equations for simplicity.

The expression of the electromagnetic radiation incident on
the spatial phase filter may now be separated into an AC-term
5   and a DC-term. If the DC-term of the field is denoted $\bar{\alpha}$, the
AC-term of the field is given by the term $e^{i\bar{\alpha}(x,y)} - \bar{\alpha}$. As the
spatial phase filter changes the phase of the DC-part of the
electromagnetic radiation by θ, the intensity of the syn-
thesized intensity pattern at the image plane of the imaging
10   system is given by:

$$I(x',y') = \left| e^{i\phi(x',y')} + \bar{\alpha}(e^{i\theta} - 1) \right|^2 \qquad (7)$$

wherein (x',y') is the coordinates of the image of the point
(x,y) of the spatial phase mask formed by the imaging system
in the image plane.

15   It should be noted that the second term of the equation is a
complex number that adds to the phasors $e^{i\phi(x,y)}$ of the spa-
tial phase mask and may be interpreted as a contrast control
parameter for the synthesized intensity pattern $I(x',y')$.

According to a preferred embodiment of the invention, the
20   average value of the phasors is adjusted in order to control
the range of intensity levels.

Instead of phase shifting the DC-part of the electromagnetic
radiation, it is also possible to synthesize a prescribed
intensity pattern by phase shifting other parts of the elec-
25   tromagnetic radiation by adapting the spatial phase filter to
phase shift electromagnetic radiation incident upon one or
more arbitrary regions of the phase filter and leaving the
phase of the remaining part of the electromagnetic radiation
unchanged and then superimposing the two parts of the elec-
30   tromagnetic radiation. The corresponding mathematics and the
corresponding design procedures for the spatial phase mask

and spatial phase filter will of course be more complicated
than for the method described in the previous section.

A simple example of phase shifting a part of the electromag-
netic radiation of a spatial frequency different from the
5   zero frequency is provided by moving the DC-part of the
electromagnetic radiation to another spatial frequency in the
Fourier plane (identical to the plane of the spatial phase
filter) utilizing an optical component with an appropriate
carrier frequency (i.e. a grating or a prism) or, preferably,
10 encoding the function of a grating or a prism into the spa-
tial phase mask, and adapting the spatial phase filter to
change the phase of the electromagnetic radiation at this
spatial frequency and to leave the phase of the remaining
part of the electromagnetic radiation unchanged.

15 According to another preferred embodiment of the invention,
the phase mask is not positioned in the back focal plane of
the lens but in the Fresnel region of the lens instead. In
this case, the electromagnetic field at the phase filter will
be given by a Fresnel transformation of the electromagnetic
20 field at the spatial phase mask. This further complicates the
mathematics and the design procedures, for example the term $\overline{\alpha}$
in equation (7) has to be substituted by the value of the
Fresnel transformation at the point(s) of phase changes of
the phase filter. However, the Fresnel transformation may be
25 calculated from a Fourier transformation by multiplication of
the phasor values of the spatial phase mask by a quadratic
phase factor followed by a Fourier transformation.

It is an important aspect of the present invention that each
intensity level of the synthesized intensity pattern for each
30 resolution element may be generated by at least two different
phasor values of a resolution element of the spatial phase
mask.

For example, when the spatial phase filter phase shifts the DC-part of the electromagnetic radiation, it will be shown later that, advantageously, the average $\bar{\alpha}$ of the phasors of the resolution elements of the phase mask should be equal to ½ and the value of the phase shift θ should be equal to π. In this case, the intensity of the synthesized image pattern at the image (x',y') of the resolution element (x,y) will be given by:

$$I(x',y') = 2(1 - \cos\phi(x',y')) \qquad (8)$$

It is seen that complex conjugate phasors (values of ϕ of opposite sign) result in identical intensity levels $I(x',y')$. It can be shown that for any value of the modulus of the average of the phasors $|\bar{\alpha}|$, two phasors exist that will generate identical intensity levels of the synthesized intensity pattern.

Further, if the spatial phase filter phase shifts parts of the electromagnetic radiation different from the DC-part, the phasor value that generates a specific intensity level will depend on the position of the resolution element in question, i.e. the phasor value and the position of the resolution element with that phasor value together define the intensity level at the image of the resolution element in the synthesized intensity pattern. Still, it is true that for each resolution element of the spatial phase mask, each intensity level of the synthesized intensity pattern may be represented by one of two different phasors of complementary phase values.

This freedom of being able to select, for each intensity level to be generated and for each resolution element of the spatial phase mask, one of two phasors is used to control the phase of the Fourier transform of the phasors at specific spatial frequencies by selection of phasors with appropriate phase values to ensure two intervals of biunique functional

dependence between phasor values and corresponding intensity values.

This freedom of choice of phasors may be utilized to select phasors of neighbouring resolution elements of the spatial phase mask with a maximum difference between them, thereby generating an electromagnetic radiation emitted from the phase mask with a maximum content of high spatial frequencies which will generate a good separation of the DC part of the electromagnetic radiation from its AC part. However, any other strategy of selecting between two possible phasor values of each resolution element may be chosen to generate a desired spatial frequency content of the electromagnetic radiation.

Preferably, the phase of the Fourier transform of the phasors at specific spatial frequencies is adjusted in order to control whether the relation between each phasor and the corresponding intensity level is a monotonic increasing or a monotonic decreasing function.

Below, a set of different methods are described that are provided according to the present invention for adjustment of the modulus of the Fourier transform of the phasors at specific spatial frequencies to attain a prescribed value. If convenient, the methods may be combined.

According to one of the methods, the individual phasors of the resolution elements of the phase mask are adjusted by a constant value until the desired value of the modulus of the Fourier transform of the phasors at specific spatial frequencies is attained while maintaining prescribed relative intensity levels between intensities of resolution elements of the intensity pattern, i.e. iteratively.

According to another method, the individual phasors of the resolution elements of the phase mask are adjusted utilizing histogram techniques known from image processing. A histogram

is a bar chart showing the number of resolution elements of the synthesized intensity pattern with a specific intensity value as a function of the intensity value. Any histogram technique, such as histogram equalization, adapting the

5 histogram to a predetermined distribution, etc., may be used iteratively until the modulus of the Fourier transform of the phasors at specific spatial frequencies attain the prescribed value.

According to yet another method, the phasor pattern of the

10 phase mask is spatially scaled in order to adjust the modulus of the Fourier transform of the phasors at specific spatial frequencies.

According to still another method, the modulus of the Fourier transform of the phasors at specific spatial frequencies is

15 adjusted utilizing half tone coding techniques, such as raster techniques, area ratio modulation, spot diameter modulation, etc.

It is seen from the description above that the intensity levels may differ from one synthesized intensity pattern to

20 the next as a consequence of the adjustments of the modulus of the Fourier transform of the phasors at specific spatial frequencies. Thus, it is preferred to control the power of the radiation source in dependence of the intensity range of the intensity pattern so that a sequence of different inten-

25 sity patterns show uniform intensity levels.

According to a preferred embodiment of the invention, the shape of the phase filter is adapted to match the spatial frequency content of the phasors of the spatial phase mask, e.g. to optimize the desired separation of the part of the

30 electromagnetic radiation to be phase filtered from the remaining part of the electromagnetic radiation.

It is within the scope of the present invention that the
imaging system further comprises zooming means for variable
scaling of the synthesized intensity pattern. The zooming of
the imaging system may be dynamically controllable, e.g. in
5   response to the scaling of the pattern of phasor values of
the phase mask.

According to the present invention, the power of the radi-
ation source may be controllable in response to the spatial
scaling of the pattern in the phase mask and/or the zooming
10   of the focusing system.

In order to provide a compact and integrated system according
to the present invention, the optical function of a Fourier-
transforming lens is encoded into the phasors of the spatial
phase mask. The Fourier transforming lens may be refractively
15   or diffractively encoded into the phase mask.

Similarly, the optical function of an output lens may be
encoded into the phase filter either refractively or
diffractively.

Further, a compensation may be encoded into the phasor values
20   of the spatial phase mask so that part of the electromagnetic
radiation modulated by the phase mask has a substantially
flat intensity profile in the image plane. Without this
compensation, part of the electromagnetic radiation modulated
by the phase mask will have a flat profile with perturbations
25   resulting from the phase filtering superpositioned upon it.
This may cause "ringings" (oscillations) at the edges of the
synthesized intensity pattern.

According to another preferred embodiment of the invention,
the source of electromagnetic radiation comprises one or more
30   light sources of different wavelengths corresponding to three
different colours, such as red, green and blue, for gener-
ation of intensity patterns of arbitrary colours. Further,
several independent systems each one illuminated by its own

wavelength can be combined into a single multi-wavelength system.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1   shows a 4f optical system for phase contrast imaging,

5   Fig. 2   shows a 2f optical system for phase contrast imaging,

Fig. 3   shows a 1f optical system for phase contrast imaging,

Fig. 4   shows (A) off-axis read-out of reflective SLM and (B) on-axis read-out of reflective SLM.

Fig. 5   shows schematically an example of a prescribed inten-
10   sity pattern in 1D.

Fig. 6   shows schematically the resulting phase encoding corresponding to Fig. 5.

DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Fig. 1 shows a 4f phase contrast imaging system (1). A laser
15   (2) emits a light beam which is expanded by a beam expander (3) into a plane light wave of uniform intensity and directs it towards a spatial phase mask (4). The light beam is trans- mitted through the spatial phase mask (4) and a Fourier transforming lens (5). The spatial phase mask is positioned
20   in the front focal plane of the lens (5) and a spatial phase filter (6) is positioned in the back focal plane of the lens (5) that is also the front focal plane of a lens (7). The Fourier transforming lenses (5, 7) need not have identical focal lengths. Different focal lengths lead to a magnifica-
25   tion ratio different from one. The phase filter (6) phase shifts the zero order diffraction part (8) of the light phase modulated by the spatial phase mask (4). The synthesized intensity pattern is generated in the back focal plane (9) of

the lens (7) and a dynamic focusing system (10) images the
synthesized intensity pattern onto a focusing plane (11).

The optical system is controlled by a computer (12). The
computer (12) comprises interface means for addressing each
5   of the resolution elements of the phase filter (4) and trans-
mitting a phasor value to the addressed resolution element.
Further, the computer (12) comprises laser control means for
controlling the power of the laser (2) and imaging control
means for controlling the focusing and the image ratio of the
10 dynamic focusing system (10). The computer (12) also com-
prises input means, such as a keyboard, a diskette drive, an
optical disc drive, a network interface, a modem, etc, for
receiving an image pattern to be synthesized by the system
(1). From the received image pattern, the computer is adapted
15 to calculate phasor values to be transmitted to the resol-
ution elements of the phase mask, e.g. based on a histogram
technique as described herein. Optionally, the phase shift of
the phase filter (6) is adjustable and controllable by
optional phase control means of the computer (12) which may
20 be further adapted to adjust the phase shift, e.g. utilizing
equation (18).

Fig. 2 shows a 2f phase contrast imaging system (20). A laser
(21) emits a light beam which is expanded by a beam expander
(22) into a plane light wave of uniform intensity and directs
25 it towards a spatial phase mask (23) and a polarization beam
splitter (24) and a quarter-wave plate (25). The polarization
beam splitter (24) and the quarter-wave plate (25) allows
beam-splitting of light of a specific linear polarization
without the power loss associated with conventional beam-
30 splitters due to splitting of the beam in both directions of
transmission through the beam-splitter. After transmission
through the polarization beam splitter (24) and the quarter-
wave plate (25), the light beam is transmitted through a
Fourier transforming lens (26) and is reflected from a spa-
35 tial phase filter (27). The spatial phase mask (23) is posi-
tioned in the front focal plane of the lens (26) and the

spatial phase filter (27) is positioned in the back focal plane of the lens (26). The phase filter (27) phase shifts the zero order diffraction part (28) of the light that is phase encoded by the spatial phase mask (23). The synthesized

5 intensity pattern is generated in the back focal plane (29) of the lens (26) and a dynamic focusing system (30) images the synthesized intensity pattern onto a focusing plane (31). As described for the system shown in Fig. 1, the system (20) is controlled by a computer (32).

10 Fig. 3 shows a 1f phase contrast imaging system (40). A laser (41) emits a light beam which is expanded by a beam expander (42) into a plane light wave of uniform intensity and directs it towards a spatial phase mask (43). The light beam is transmitted through the spatial phase mask (43) and an image

15 forming lens (44). A phase filter (45) positioned in the back focal plane of the lens (44) phase shifts the zero order diffraction part of the light phase encoded by the spatial phase mask (43). The synthesized intensity pattern is gener-ated in the image plane (46) of the lens (44) and a dynamic

20 focusing system (47) images the synthesized intensity pattern onto a focusing plane (48). As described for the system shown in Fig. 1, the system (40) is controlled by a computer (49).

Fig. 4 shows details of (A) an off-axis read-out of a reflec-tive phase mask (50) (or a spatial light modulator) and of

25 (B) an on-axis read-out of a reflective phase mask (51) with a beam splitter (52). Both configurations (A, B) may be utilized in the systems shown in Figs. 1-3.

PHASE ENCODING FOR DC PHASE FILTERING

In the following an example of encoding a spatial phase mask and a spatial phase filter will be given based on a system filtering in the DC-frequency range. The system chosen in this example is based on a 4-f lens configuration as shown in Fig. 1 and illuminated by electromagnetic radiation in the visible frequency domain, hereafter simply denoted as *light* radiation.

Assuming that the illuminating light is monochromatic and has a substantially flat amplitude profile we obtain the following spatial amplitude distribution emitted from the spatial phase mask:

$$a(x, y) = \text{rect}\left(\frac{x}{\Delta x}, \frac{y}{\Delta y}\right) \exp(i\phi(x, y)) \qquad (9)$$

where $\alpha(x, y) = \exp(i\phi(x, y))$ represent the spatially encoded phasor values and $\Delta x \Delta y$ is the area of the input phase modulating spatial light modulator.

It turns out to be convenient to separate $\alpha(x, y)$ into two terms describing a spatially invariant DC-value, $\overline{\alpha}$, and a spatially varying AC-contribution $\Delta \alpha(x, y)$. The DC-value can be found as:

$$\overline{\alpha} = \frac{1}{\Delta x \Delta y} \iint_{\Delta x \Delta y} \exp(i\phi(x, y)) dx dy \qquad (10)$$

Subsequently the AC-term is expressed by:

$$\Delta \alpha(x, y) = \exp(i\phi(x, y)) - \frac{1}{\Delta x \Delta y} \iint_{\Delta x \Delta y} \exp(i\phi(x, y)) dx dy \qquad (11)$$

The separation of $\alpha(x, y)$ into a spatially invariant DC-term and a spatially varying AC-term is an important point and will be used throughout the remaining part of this example, especially in the description of the spatial filtering procedure.

The spatial filter utilized in this example is chosen as a circular phase contrast filter (different transverse shapes can also be used) centered around origo in the the spatial frequency domain, denoted by coordinates (f_x, f_y):

$$T(f_r) = 1 + (\exp(i\theta) - 1)\text{circ}\left(\frac{f_r}{\Delta f_r}\right) \qquad (12)$$

where $f_r = \sqrt{f_x^2 + f_y^2}$ denotes radial spatial frequency and Δf_r describes the size of the circular (circ) phase filter.

In the spatial frequency domain (the filtering plane) the Fourier transformation ($\mathfrak{I}$) of the spatially modulated light radiation from the spatial phase mask is present. The filtering operation on the Fourier transformed light radiation performed by the spatial phase contrast filter can be expressed as a simple point-by-point multiplication procedure. Subsequently the spatially filtered light is inverse Fourier transformed ($\mathfrak{I}^{-1}$) by the second Fourier lens (Fourier transformation and reflected output coordinates) and the resulting spatial amplitude distribution in the image plane (with coordinates (x', y')) can accordingly be written as:

$$\phi(x', y') = a(x', y') + (\exp(i\theta) - 1)\mathcal{F}^{-1}\left(\mathcal{I}(a(x, y))\mathrm{circ}\left(\frac{f_r}{\Delta f_r}\right)\right)$$

$$\cong a(x', y') + \overline{a}(\exp(i\theta) - 1)\mathrm{rect}\left(\frac{x'}{\Delta x}, \frac{y'}{\Delta y}\right) \qquad (13)$$

$$= \left[\exp(i\phi(x', y')) + \overline{a}(\exp(i\theta) - 1)\right]\mathrm{rect}\left(\frac{x'}{\Delta x}, \frac{y'}{\Delta y}\right)$$

Within the illumination-region, $(x', y') \in \mathfrak{R}'$, outlined by

$\mathrm{rect}\left(\dfrac{x'}{\Delta x}, \dfrac{y'}{\Delta y}\right)$, one obtains:

5

$$|\phi(x', y')|^2 \cong 1 + 4|\overline{a}|\sin\left(\frac{\theta}{2}\right)\left[|\overline{a}|\sin\left(\frac{\theta}{2}\right) - \sin\left(\phi_{\overline{a}} - \phi(x', y') + \frac{\theta}{2}\right)\right] \quad (14)$$

Requiring that $|\phi(x'_o, y'_o)|^2 \equiv 0$ corresponding to complete darkness as the lowest intensity level in

10 regions $(x'_o, y'_o) \in \mathfrak{R}'_o$ implies:

$$1 + 4|\overline{a}|\sin\left(\frac{\theta}{2}\right)\left[|\overline{a}|\sin\left(\frac{\theta}{2}\right) - \sin\left(\phi_{\overline{a}} - \phi_o + \frac{\theta}{2}\right)\right] = 0 \qquad (15)$$

where the abbreviation $\phi_o = \phi(x'_o, y'_o)$ has been used.

15

The solutions to Eq. (15) are given by:

$$|\overline{a}| = \frac{\sin\left(\phi_{\overline{a}} - \phi_o + \frac{\theta}{2}\right) \pm \sqrt{\sin^2\left(\phi_{\overline{a}} - \phi_o + \frac{\theta}{2}\right) - 1}}{2\sin\left(\frac{\theta}{2}\right)} \qquad (16)$$

20 The requirement $o < |\overline{a}| < 1$ implies that:

24

$$\sin^2\left(\phi_{\bar{a}} - \phi_o + \frac{\theta}{2}\right) = 1 \Rightarrow \qquad (17)$$

$$\theta = \pi - 2(\phi_{\bar{a}} - \phi_o) + p2\pi, \qquad p = 0, \pm 1, \pm 2, \ldots$$

leading to

$$|\overline{\alpha}| = \frac{\pm 1}{2\sin\left(\dfrac{\theta}{2}\right)} \quad \Rightarrow \quad \frac{1}{2} \le |\overline{\alpha}| < 1 \qquad (18)$$

5

where the +sign is for θ-values in the interval:

$$\theta \in \left]\frac{\pi}{3} ; \frac{5\pi}{3}\right[+ p_{even}2\pi \qquad (19)$$

10 and the -sign is for θ-values:

$$\theta \in \left]\frac{\pi}{3} ; \frac{5\pi}{3}\right[+ p_{odd}2\pi \qquad (20)$$

The corresponding interval for $\left(\phi_{\bar{a}} - \phi_o\right)$ is:

15

$$\left(\phi_{\bar{a}} - \phi_o\right) \in \left]\frac{\pi}{3} ; -\frac{\pi}{3}\right[\qquad (21)$$

Inserting the expression for $|\overline{\alpha}|$, one obtains the simple intensity expression:

20

$$|\alpha(x', y')|^2 = 2\left[1 \mp \sin\left(\phi_{\bar{a}} - \phi(x', y') + \frac{\theta}{2}\right)\right] \qquad (22)$$

where

$$\iint\limits_{\Delta x \Delta y} \exp(i\phi(x, y))dxdy = \Delta x \Delta y |\overline{\alpha}| \exp(i\phi_{\bar{a}}) \qquad (23)$$

The phase-only transformations imply that energy is conserved:

$$\iint\limits_{\Delta x \Delta y} |\alpha(x', y')|^2 dx'dy' = \iint\limits_{\Delta x \Delta y} |a(x, y)|^2 dxdy = \Delta x \Delta y \qquad (24)$$

A special case:

The most convenient choice for $\bar{\alpha}$ is: $\bar{\alpha} = \dfrac{1}{2}$ (implying that $\theta = \pi + p_{even} 2\pi$), so that the output intensity can be described as:

$$|\alpha(x', y')|^2 = 2\left[1 - \cos(\phi(x', y'))\right] \qquad (25)$$

In this case the phase→intensity mapping is described by the intervals $[0; \pi] \rightarrow [0;4]$.

By setting $\bar{\alpha} = \dfrac{1}{2}$ one obtains the following requirement to the phase function $\phi(x, y)$:

$$\begin{cases} \iint\limits_{\Delta x \Delta y} \cos(\phi(x, y))dxdy = \dfrac{\Delta x \Delta y}{2} \\ \iint\limits_{\Delta x \Delta y} \sin(\phi(x, y))dxdy = 0 \end{cases} \qquad (26)$$

Inserting the expression for $|\alpha(x', y')|^2$ in Eq. (24) yields:

$$2 \iint\limits_{\Delta x \Delta y} \left[1 - \cos(\phi(x', y'))\right]dx'dy' = \Delta x \Delta y \qquad (27)$$

in accordance with the first of the integral expressions in Eq. (26).

Encoding procedure:

- A given intensity distribution (image) $|\alpha(x', y')|^2$ is desired at the output side of the optical setup.

5

- Pixellation of the image, that is generally represented in the greyscale range: $[0; gmax]$, provides the relation:

$$\iint |\alpha(x', y')|^2 dx' dy' = \Delta x \Delta y \Rightarrow \sum_{ij} |\alpha(i, j)|^2 = \frac{gmax}{4} \# \, pix_{(\Delta x \Delta y)} \, .$$

10

- The histogram for the desired image $|\alpha(i, j)|^2$ is adjusted (adj) within the greyscale range $[0; gmax]$, so that the previous point is fulfilled:

$$|\alpha(i, j)|^2 \rightarrow |\alpha(i, j)|^2_{adj} \, .$$

15

- The phase values can now be calculated as:

$$\phi(i, j) = \arccos\left(1 - \frac{2|\alpha(i, j)|^2_{adj}}{gmax}\right) \, .$$

- As before pixellation provides the relation:

$$\sum_{ij} \sin(\phi(i, j)) = 0 \, .$$

20

- The previous point can now be fulfilled by complex conjugating half the input pixels having the same phase value in the phase histogram.

25

- The phase conjugate phase flipping provides a valuable tool (an extra degree of freedom) for manipulating the spatial frequency content in order to optimize the

separation of low and high frequency terms at the filter plane.

- The scheme is robust to constant phase errors across the input spatial phase modulator, since Eq. (22) is a function of the difference: $\phi_{\bar{\alpha}} - \phi(i, j)$, only. Furthermore, small variations in the individual pixel phase values do not introduce any detrimental effects because the average value $\bar{\alpha}$, is a result of a very large phasor sum.

- If the desired intensity distribution is too small to include all energy, that is, the histogram is scaled to maximum and the left hand side of Eq. (24) is still smaller than the right hand side, then the input phase object can be scaled until Eq. (24) is fulfilled. In order to obtain a scale invariant output intensity level a dynamic focusing system is needed. Similarly, intensity invariance can be obtained by controlling the radiated power from the light source. Alternatively, one can ignore the residual background illumination and obtain intensity levels with a gain factor of 9^- (background constant equal to 1^-) for narrow generally shaped line structures (e.g. Eq. (14)).

Example 1:
A very simple example illustrating the individual steps in the above procedure will be given below. To simplify the example it will be considered in one dimension only. The starting point for encoding the spatial phase mask in this example is based on the following parameters:

$$\begin{cases} \overline{\alpha} = 0.5 \\ \theta = \pi \\ \# \, pix_{(\Delta x)} = 14 \\ gmax = 4 \end{cases} \qquad (28)$$

Consider the pixellated 3-step function shown in Fig. 5 to be synthesized in the image plane as an intensity distribution. From the above choices of parameters one obtains the simple relation between phase values in the spatial phase mask and the image intensity values:

$$|o(i)|^2 = 2[1 - \cos(\phi(i))] \qquad (29)$$

To proceed from here it necessary to calculate the accumulated intensity $\sum_i |o(i)|^2$ in the image to be synthesized. The accumulated intensity is easily calculated from an image histogram where the x-axis represents greylevel value and the y-axis represents the amount of pixels in the image at a given greylevel value. By use of a histogram $\sum_i |o(i)|^2$ is simply found as the weighted sum of all greylevel values (x-axis) multiplied by their pixel counting (y-axis). This describes, so to speak, the "weight" of the image. In this simple example histogram calculations are not needed since we only have 3 greylevels with well-defined separations.

The value for the accumulated intensity has to obey the equality:

$$\sum_i |o(i)|^2 = \frac{gmax}{4} \# \, pix_{(\Delta x)} = \# \, pix_{(\Delta x)} = 14 \qquad (30)$$

From Fig. 5 we obtain:

$$\sum_i \left| \alpha(i) \right|^2 = 4 pixels \cdot 0 + 4 pixels \cdot (0.5 max) + 6 pixels \cdot max = 8 max \tag{31}$$

So that the value for *max* can be estimated to be:

$$max = \frac{7}{4} \tag{32}$$

The corresponding adjusted intensity levels, $\left| \alpha(i) \right|^2_{adj}$, are therefore: 7/4, 7/8 and 0. These values can now be utilized to calculate the phase values of the spatial phase mask from the relation:

$$\phi(i) = \arccos\left(1 - \frac{2\left|\alpha(i)\right|^2_{adj}}{gmax}\right) = \arccos\left(1 - \frac{\left|\alpha(i)\right|^2_{adj}}{2}\right) \tag{33}$$

where from we obtain the three phase values: 1.45 rad. 0.97 rad. and 0 rad.

The last step needed in order to encode the spatial phase mask is that the following equality is fulfilled:

$$\sum_i \sin(\phi(i)) = 0 \tag{34}$$

Since we have the choice to use complex conjugate phasor values (two phasors giving the same intensity level) many approaches can be taken from here. A simple approach is to flip every second phasor with its complex conjugate value as shown in Fig. 6. The final phase values used in the phase mask are accordingly: ± 1.45 rad. ± 0.97 rad. and 0 rad.

As the last step we can check whether the criteria: $\bar{\alpha} = 1 / 2$, is actually fulfilled with the chosen phasor encoding:

$$\bar{\alpha} = \frac{1}{14} \left(4 \exp(i0) + 2 \exp(i0.97) + 3 \exp(i1.45) + 2 \exp(-i0.97) + 3 \exp(-i1.45) \right) \equiv 1 / 2$$

$$(35)$$

GENERAL PHASE CORRECTION PROCEDURE INTEGRATED WITH THE
PHASE ENCODING

In Eq. (14) we obtained an analytic relation between the phase values in the spatial phase mask and the resulting intensity distribution, within the region $(x', y') \in \mathfrak{R}'$:

$$\left|o(x', y')\right|^2 \cong 1 + 4|\overline{\alpha}| \sin\left(\frac{\theta}{2}\right)\left[|\overline{\alpha}| \sin\left(\frac{\theta}{2}\right) - \sin\left(\phi_{\overline{a}} - \phi(x', y') + \frac{\theta}{2}\right)\right] \quad (36)$$

The analysis leading to the above relation was based on the assumption that $|\overline{\alpha}|$ is a constant value within the $\mathfrak{R}'$-domain. In other words, the following approximation was applied:

$$\mathfrak{T}^{-1}\left(\mathfrak{T}(a(x, y))\mathrm{circ}\left(\frac{f_r}{\Delta f_r}\right)\right) \cong \overline{\alpha}\,\mathrm{rect}\left(\frac{x'}{\Delta x}, \frac{y'}{\Delta y}\right) \quad (37)$$

However, for certain spatial filter parameters the lefthand side of this expression will not be a space invariant constant value throughout the whole $\mathfrak{R}'$-domain but will instead manifest slowly variations/oscillations. This will introduce small errors in the final superposition between the phase filtered DC-value and the direct propagated AC-signal. In order to circumvent this problem a technique is needed that can counteract the distortions by use of phase-only encoding in the components already present in the system. In what follows a procedure for integrating predistortion that counteracts the above mentioned distortions will be described that is purely based on modifying the phasor values in the spatial phase mask at the input side of the system. The method can also counteract other types of distortions inherent in a practical implementation of the

system. Furthermore, the method can be applied in systems filtering at other spatial frequencies than DC.

Procedure:

5 When encoding the input phase function it is helpful to have a reverse equation, expressing the input phase distribution as a function of an adjusted (electronic) image grey-level distribution, I_{slm}, addressing the input spatial light modulator:

10

$$\frac{4I_{slm}}{gmax} \cong 1 + 4|\bar{\alpha}(x', y')| \sin\left(\frac{\theta}{2}\right)\left[|\bar{\alpha}(x', y')| \sin\left(\frac{\theta}{2}\right) - \sin\left(\phi_{\bar{\alpha}}(x', y') - \phi(x', y') + \frac{\theta}{2}\right)\right]$$

(38)

where it has been taken into account that $\bar{\alpha}(x', y')$ is not

15 considered as a constant but manifests a smooth oscillating behaviour within the optical image domain. The maximum value of I_{slm} is denoted $gmax$.

Now, one can derive a formula for the grey-level

20 correction, $\Delta I_{slm}(x', y')$, that one needs to apply in order to encode a phase function that compensates for the spatial variation of the average phase value $\bar{\alpha}(x', y')$:

$$\begin{cases} \dfrac{4I_{slm}(x', y')}{gmax} \cong 1 + 4|\bar{\alpha}(x', y')| \sin\left(\frac{\theta}{2}\right)\left[|\bar{\alpha}(x', y')| \sin\left(\frac{\theta}{2}\right) - \sin\left(\phi_{\bar{\alpha}}(x', y') - \phi(x', y') + \frac{\theta}{2}\right)\right] \\ \phi(x', y') = a\cos\left(1 - \dfrac{2(I_{slm}(x', y') + \Delta I_{slm}(x', y'))}{gmax}\right) \end{cases}$$

(39)

25

where the second relation has been derived from the first by setting $\bar{\alpha} = 1 / 2$ and $\theta = \pi$.

30 By inserting the second relation in the first expression one gets:

$$\Delta I_{slm}(x', y') = \left(\frac{1}{2\overline{|\alpha(x', y')|}} - 1\right) I_{slm}(x', y') - \frac{gmax}{2\overline{|\alpha(x', y')|}} \left(\overline{|\alpha(x', y')|} - \frac{1}{2}\right)^2$$

(40)

5 This formula is however not directly useful because it is related to the histogram adjusted grey-level distribution denoted by I_{slm}.

One needs a formula that relates the above correction
10 term to the original input grey-level distribution $I(x, y)$ that has not been modified by histogram adjustments. This is important since the effect of the grey-level corrections also have to be incorporated in the procedure of histogram adjustments.

15
The histogram scaling gives:

$$I(x, y) = \frac{I_{max}}{I_{slm,max}} I_{slm}(x, y)$$

(41)

20 where I_{max} and $I_{slm,max}$ are the maximum grey-level values occurring in the original and the adjusted electronic grey-level distributions respectively.

Similarly, one can apply this relation to the intensity
25 correction term ΔI_{slm} and obtain:

$$\tilde{I}(x, y) = I(x, y) + \Delta I(x, y) = \frac{I_{max}}{I_{slm,max}} \left(I_{slm}(x, y) + \Delta I_{slm}(x, y)\right)$$

(42)

resulting in:

30

$$\tilde{I}(x, y) = \frac{1}{2|\overline{\alpha}(x, y)|}\left(I(x, y) - gmax\,\frac{I_{max}}{I_{sim,max}}\left(\left|\overline{\alpha}(x, y)\right| - \frac{1}{2}\right)^2\right) \quad (43)$$

In order to have enough dynamic range in grey-levels for the correction term one can derive an inequality from the above relation by using the fact that $\tilde{I}_{max} \leq gmax$:

$$\frac{1}{2|\overline{\alpha}_{min}|}\left(I_{max} - gmax\,\frac{I_{max}}{I_{sim,max}}\left(\left|\overline{\alpha}_{min}\right| - \frac{1}{2}\right)^2\right) \leq gmax \quad (44)$$

or

$$I_{max} \leq \frac{2|\overline{\alpha}_{min}| \cdot gmax}{\left(1 - \frac{gmax}{I_{sim,max}}\left(\left|\overline{\alpha}_{min}\right| - \frac{1}{2}\right)^2\right)} \quad (45)$$

Since the first term is the dominating term in the expression for the intensity correction it will in practice be sufficient just to have the much simpler corrections:

$$\begin{cases} \tilde{I}(x, y) = \dfrac{I(x, y)}{2|\overline{\alpha}(x, y)|} \\ I_{max} \leq 2|\overline{\alpha}_{min}| \cdot gmax \end{cases} \quad (46)$$

PROPOSED APPLICATIONS:

* Laser machining, marking, branding, trimming, hardening, scribing, labeling, welding and cutting on two- and three-dimensional surfaces especially by use of CO_2 and Nd:YAG laser based systems. The main advantage is that energy is not absorbed in the system (thereby preventing damage of the optical hardware) and this nonabsorbed energy is instead utilized to increase the intensity level of the desired light distribution in the image plane. High power can be delivered to selected regions on a work piece simultanously.

* Efficient and dynamic spot-array generators based on phase contrast imaging. In order to provide bias or holding beams for arrays of optoelectronic elements, such as bistable elements, photonic switches and smart pixels.

* Generation of structured light (lossless) for machine vision applications. E.g. periodic and skew periodic mesh grid illumination that can be updated in parallel.

* Photolithographic applications (laser 3D direct writing in parallel without the need for sequential scanning). E.g. high power laser direct writing of waveguides in Ge-doped silica.

* Spatial light intensity modulation in general by use of pure phase modulation (radiation focusators).

* Laser beam shaping (dynamic).

- Highly efficient parallel image projection without the need for a laser scanning device.

5 - Dynamic Infrared Scene Projection (DIRSP).

- Exposure device for grating and mask production.

- LIDAR applications.

10

- Laserprinting in parallel.

- Lasershow applications.

15 - Atmosphere research.

CLAIMS

1. A method for synthesizing an intensity pattern with low loss of electromagnetic energy, comprising spatial modulation of electromagnetic radiation with

5   a spatial phase mask for modulation of the phase of the incident electromagnetic radiation by phasor values of individual resolution elements of the spatial phase mask, each phasor value being determined in such a way that

1)   the values of the Fourier transformed phasors attains
10   predetermined values for predetermined spatial frequencies, and

2)   the phasor value of a specific resolution element of the spatial phase mask corresponds to a distinct intensity level of the image of the resolution
15   element in the intensity pattern, and

a spatial phase filter for phase shifting of a part of the electromagnetic radiation, in combination with

an imaging system for generation of the intensity pattern by interference in the image plane of the imaging system
20   between the part of the electromagnetic radiation that has been phase shifted by the phase filter and the remaining part of the electromagnetic radiation.

2. A method according to claim 1, wherein the fact that for each resolution element of the spatial phase mask, each
25   intensity level of the synthesized intensity pattern may be represented by one of two different phasors of complementary phase values is used to control the phase of the Fourier transform of the phasors at specific spatial frequencies by selection of phasors with appropriate phase values in such a
30   way that the function defining the intensity values as a function of the phasor values comprises two regions of biunique functional dependence between phasor values and corresponding intensity values.

3. A method according to claim 1 or 2, wherein the modulus of the Fourier transform of the phasors at specific spatial frequencies is adjusted in order to control the range of intensity levels of the synthesized intensity pattern.

5   4. A method according to any of claims 1-3, wherein the phase of the Fourier transform of the phasors at specific spatial frequencies is adjusted in order to control whether the relation between each phasor and the corresponding intensity level is a monotonic increasing or a monotonic decreasing

10   function.

5. A method according to any of claims 1-4, wherein the adjustment of the modulus of the Fourier transform of the phasors at specific spatial frequencies comprises at least one of the following measures:

15   a) adjusting the individual phasors of the resolution elements of the phase mask maintaining prescribed relative intensity levels between intensities of resolution elements of the intensity pattern,

         b) adjusting the individual phasors of the resolution
20   elements of the phase mask by histogram techniques,

         c) spatially scaling the phasor pattern of the phase mask,

         d) utilizing half tone coding techniques.

6. A method according to any of claims 1-5, wherein the power
25   of the radiation source is controlled in response to the intensity range of the intensity pattern.

7. A method according to any of claims 1-6, wherein each phasor of the phase mask is selected from the set of two phasors with complementary phase values in such a way that a specific spatial frequency distribution of the intensity of the electromagnetic radiation at the spatial filter is attained.

8. A method according to claim 7, wherein the phase of phasors of adjacent resolution elements and of substantially identical phasor values alternates between the two possible complementary phase values of phasors.

9. A method according to claim 8, wherein the shape of the phase filter is adapted to match the spatial frequency content of the phasors of the spatial phase mask.

10. A method according to any of claims 1-9, wherein phasors of the phase mask and the phase shift of the phase filter are selected in such a way that the intensity level of at least one resolution element of the synthesized intensity pattern is zero.

11. A method according to any of claims 1-10, wherein the modulus of the Fourier transform of the phasors at specific spatial frequencies is adjusted, by selection of appropriate phasors of the phase mask, substantially to its minimum values to obtain a maximum dynamic range of the phasors of the phase mask.

12. A method according to any of claims 1-11, wherein the phase filter is centred around the zero-order diffraction region.

13. A method according to claim 12, wherein at least one intensity level of the intensity pattern may be represented by one of two complex conjugate phasors.

14. A method according to claim 12, wherein at least one intensity level of the intensity pattern is represented by one of two phasors with phases the sum of which equals π.

15. A method according to any of claims 10-14, wherein the modulus of average value of the phasors and the phase shift introduced by the phase filter of the zero-order diffracted electromagnetic radiation are related to each other in accordance with the equations

$$|\bar{\alpha}| = \frac{1}{2\left|\sin\frac{\theta}{2}\right|} \qquad \text{and} \qquad |\bar{\alpha}| \le 1$$

16. A method according to claim 15, wherein modulus of the average value of the phasors ranges from 0.1 to 0.9.

17. A method according to claim 15 or 16, wherein modulus of the average value of the phasors ranges from 0.25 to 0.75.

18. A method according to any of claims 15-17, wherein modulus of the average value of the phasors ranges from 0.4 to 0.6.

19. A method according to any of claims 15-18, wherein modulus of the average value of the phasors is approximately 0.5.

20. A method according to any of claims 1-19, wherein the phase shift of the phase filter ranges from $\pi/4$ to $7\pi/4$.

21. A method according to any of claims 1-20, wherein the phase shift of the phase filter ranges from $\pi/2$ to $3\pi/2$.

22. A method according to any of claims 1-21, wherein the phase shift of the phase filter ranges from $3\pi/4$ to $5\pi/4$.

23. A method according to any of claims 1-22, wherein the phase shift of the phase filter is approximately π.

24. A method according to any of claims 1-23, wherein the phase shift of the phase filter is variable.

5 25. A method according to any of claims 1-24, wherein the imaging system comprises zooming means for variable scaling of the intensity pattern.

26. A method according to claim 25, wherein the zooming of the imaging system is dynamically controllable.

10 27. A method according to claim 25 or 26, wherein the zooming of the imaging system is controllable in dependence of the scaling of the phase mask.

28. A method according to any of claims 25-28, wherein the power of the radiation source is controllable in response to 15 the spatial scaling of the pattern in the phase mask and/or the zooming of the focusing system.

29. A method according to any of claims 1-28, wherein the phase mask is a spatial light modulator.

30. A method according to any of claims 1-29, wherein the 20 optical function of a Fourier-transforming lens is encoded into the phasors of the phase mask.

31. A method according to any of claims 1-30, wherein the optical function of an output lens is encoded into the phase filter.

25 32. A method according to any of claims 1-31, wherein part of the electromagnetic radiation modulated by the phase mask has a substantially flat intensity profile in the image plane.

33. A method according to any of claims 1-32, wherein the source of electromagnetic radiation comprises one or more light sources of different wavelengths corresponding to three different colours, such as red, green and blue, for gener-
5 ation of intensity pattern of arbitrary colours.

34. A phase contrast imaging system for synthesizing an intensity pattern with low loss of electromagnetic energy, comprising

    at least one source of electromagnetic radiation for emission
10 of electromagnetic radiation,

    a spatial phase mask for modulation of the phase of the incident electromagnetic radiation by phasor values of individual resolution elements of the spatial phase mask, wherein each phasor value has been determined in such a way that

15   1) the values of the Fourier transformed phasors attains predetermined values for predetermined spatial frequencies, and

        2) the phasor value of a specific resolution element of the spatial phase mask corresponds to a distinct intensity level of the image of the resolution
20   element in the intensity pattern, and

    a spatial phase filter for phase shifting of a part of the electromagnetic radiation, and

    an imaging system for generation of the intensity pattern by
25 interference in the image plane of the imaging system between the part of the electromagnetic radiation that has been phase shifted by the phase filter and the remaining part of the electromagnetic radiation.

35. A system according to claim 34, wherein the imaging system comprises a first and a second Fourier transforming lens, the spatial phase mask being positioned in the front focal plane of the first lens, the spatial phase filter being
5   positioned at the back focal plane of the first lens, and the second lens being positioned so that its front focal plane is positioned at the position of the back focal plane of the first lens.

36. A system according to claim 34 or 35, wherein the imaging
10 system comprises one Fourier transforming lens the spatial phase filter being positioned at the back focal plane of the lens.

37. A system according to any of claims 34-36, wherein the imaging system comprises one imaging lens the spatial phase
15 filter being positioned in the back focal plane of the lens.

38. A system according to claim 34-37, further comprising a polarizing beam splitter and a quarter wave plate and/or a phase filter reflecting electromagnetic radiation incident upon it.

20 39. A system according to any of claims 34-38, wherein the spatial phase filter changes the phase of the DC-part of the electromagnetic waves and leaves the phase of the remaining part of the radiation unchanged.

40. A system according to any of claims 34-38, wherein the
25 spatial phase filter do not change the phase of the DC-part of the electromagnetic waves and changes the phase of the remaining part of the radiation.

41. A system according to any of claims 34-38, wherein the spatial phase filter blocks the DC-part of the electromag-
30 netic waves and leaves the remaining part of the radiation unchanged.

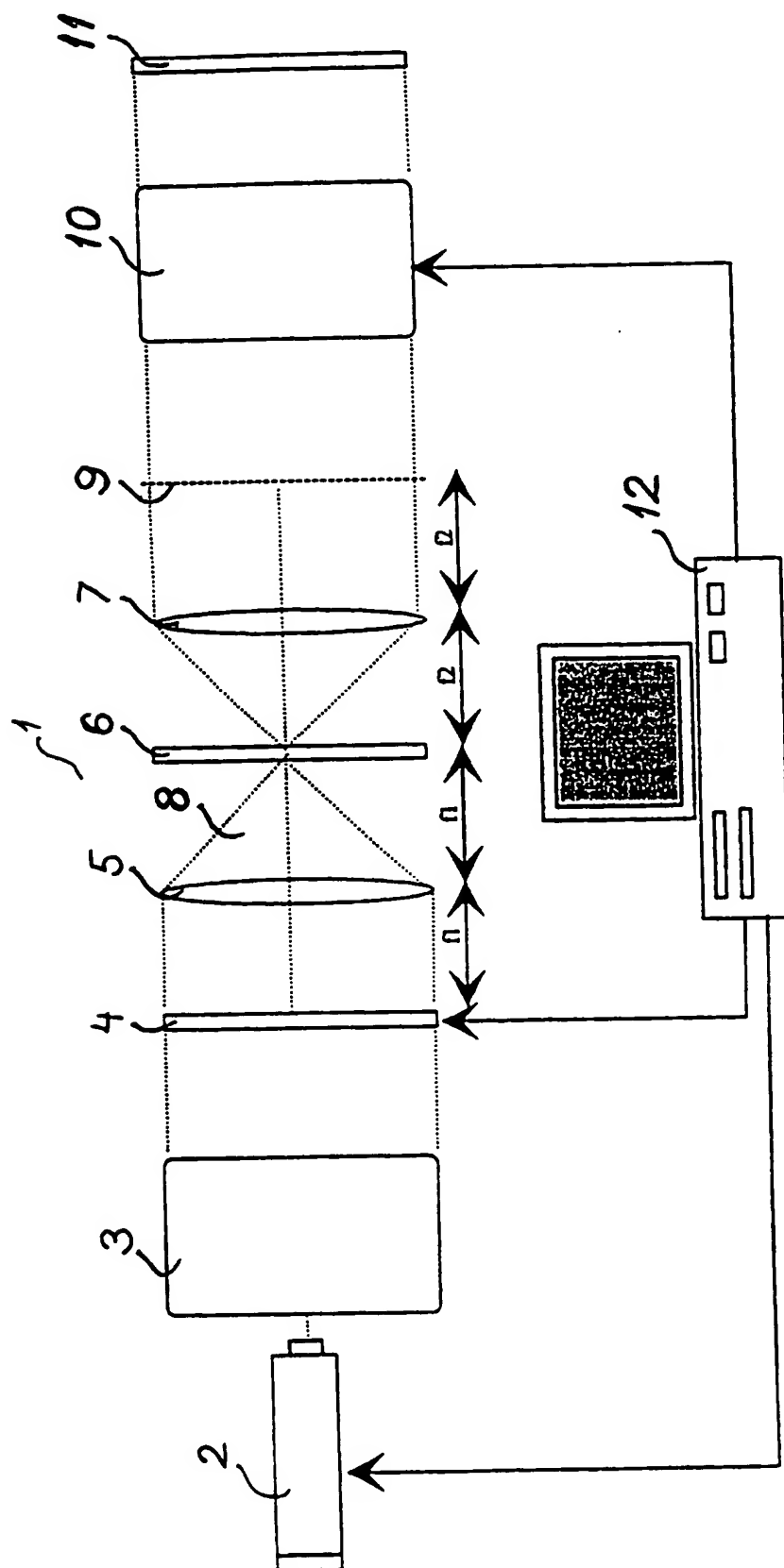42. A system according to any of claims 34-41, wherein the source of electromagnetic radiation is a Laser.
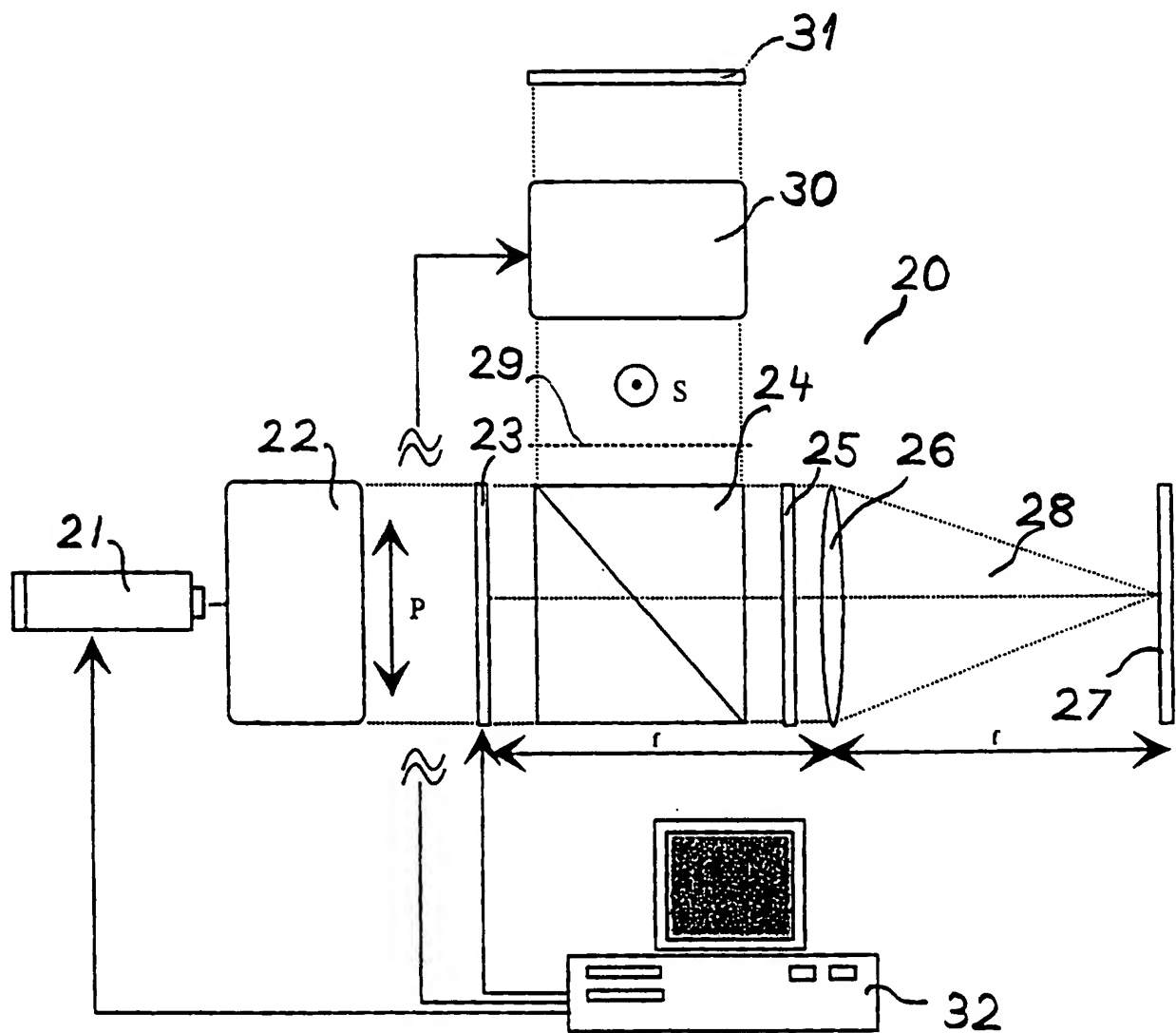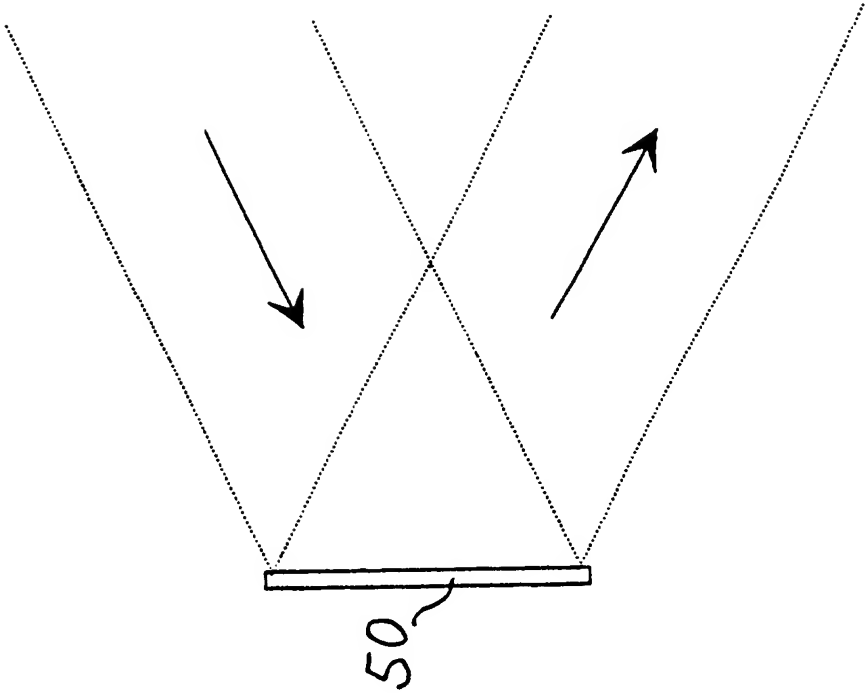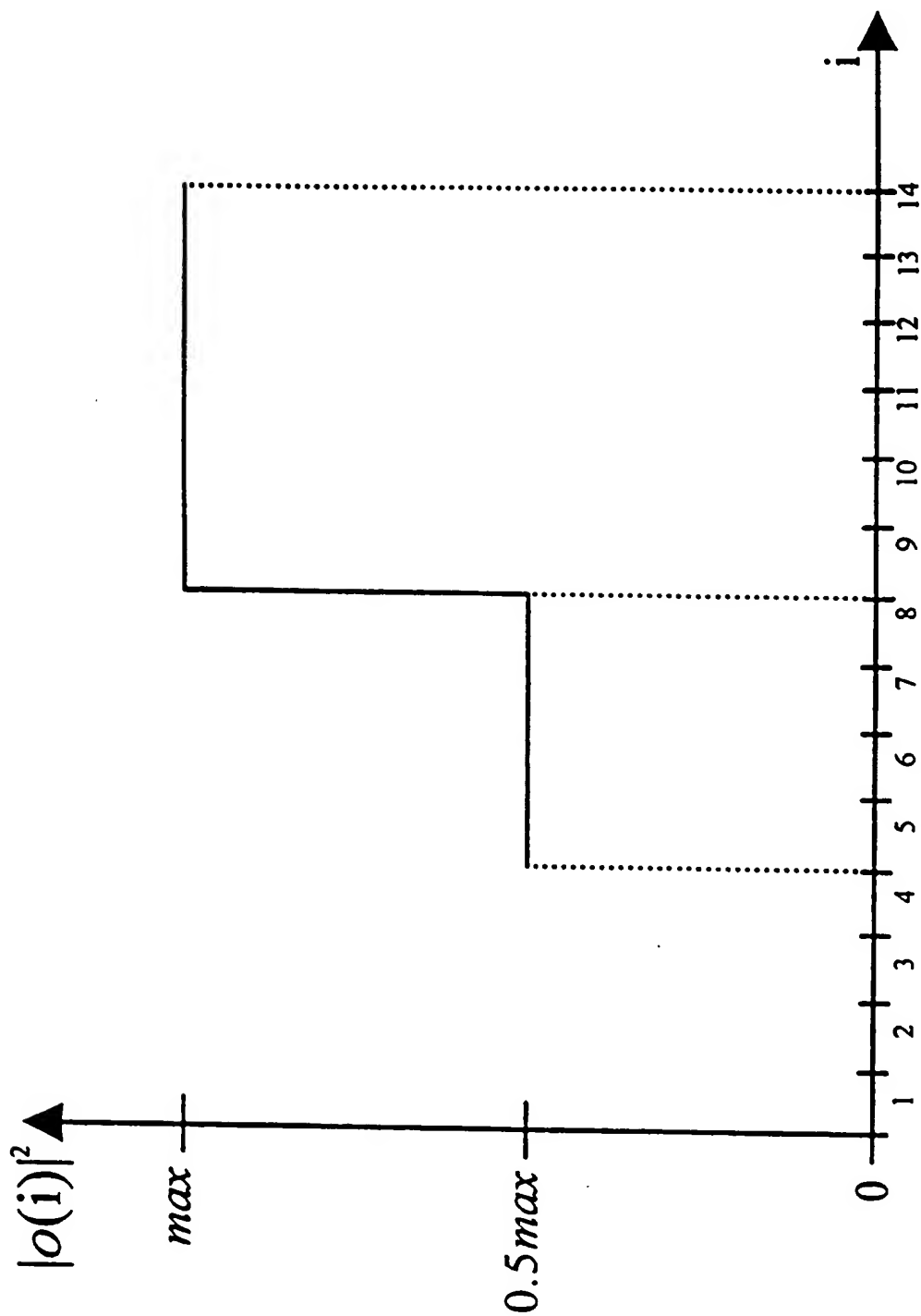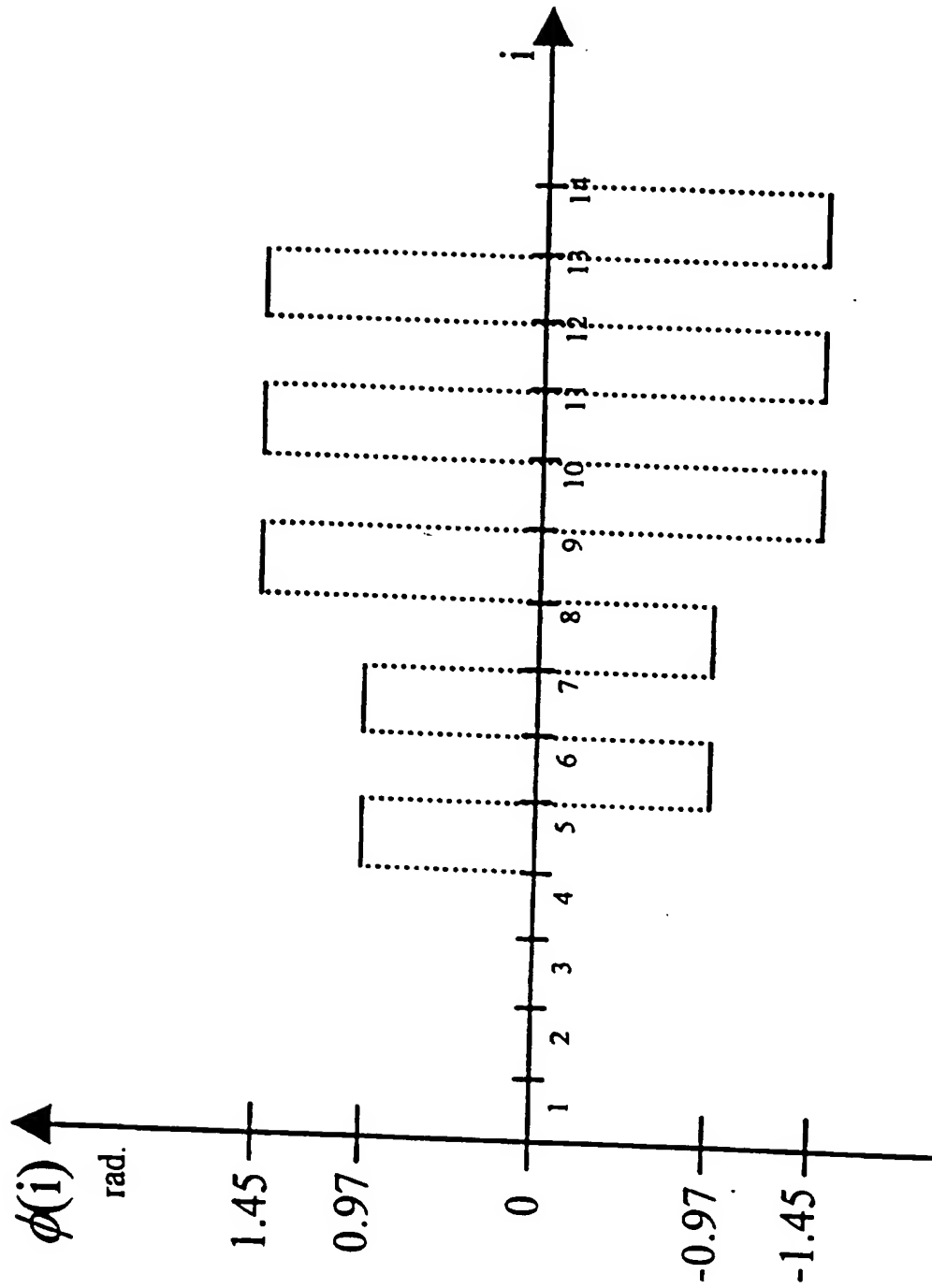
Fig. 1

Fig. 2

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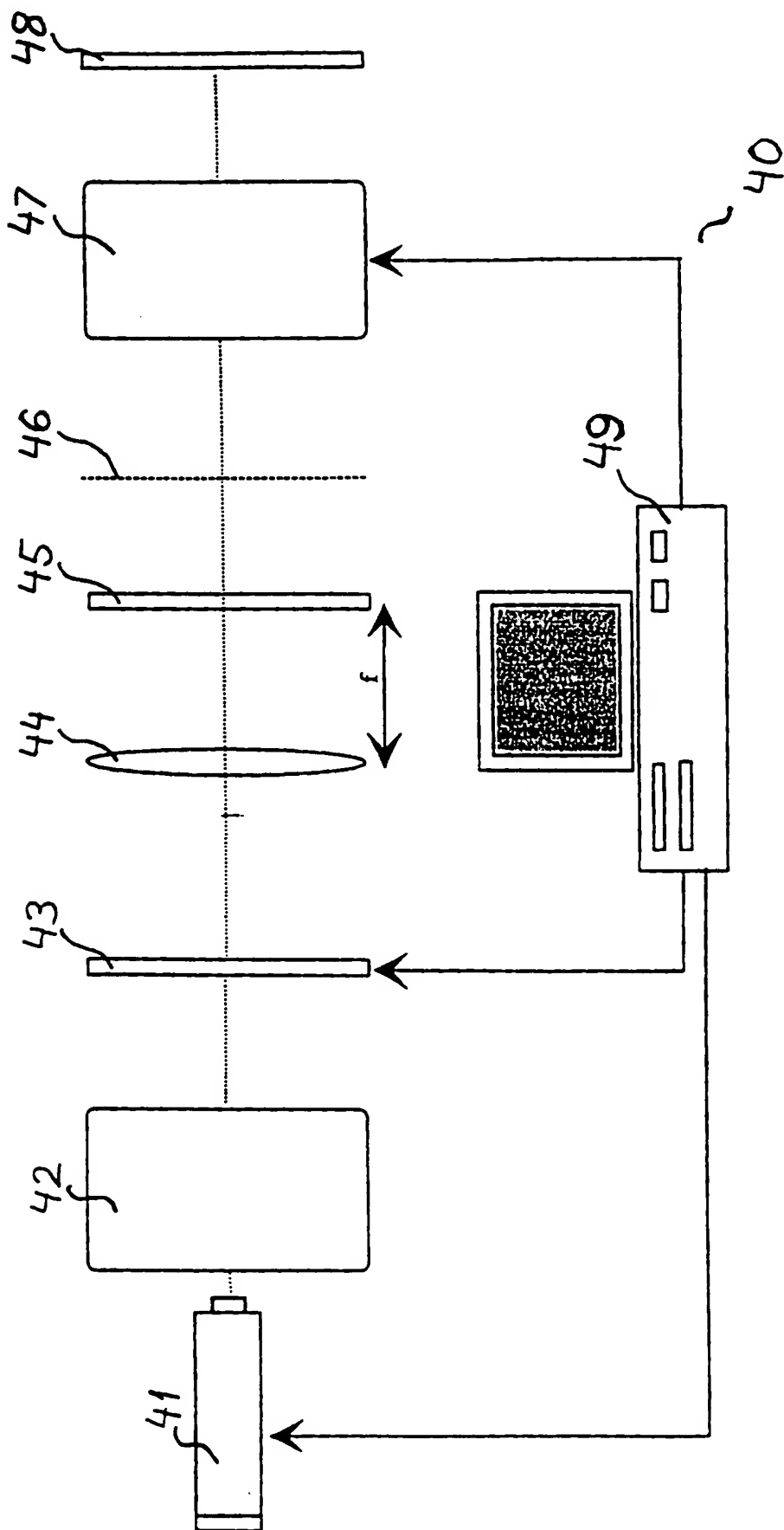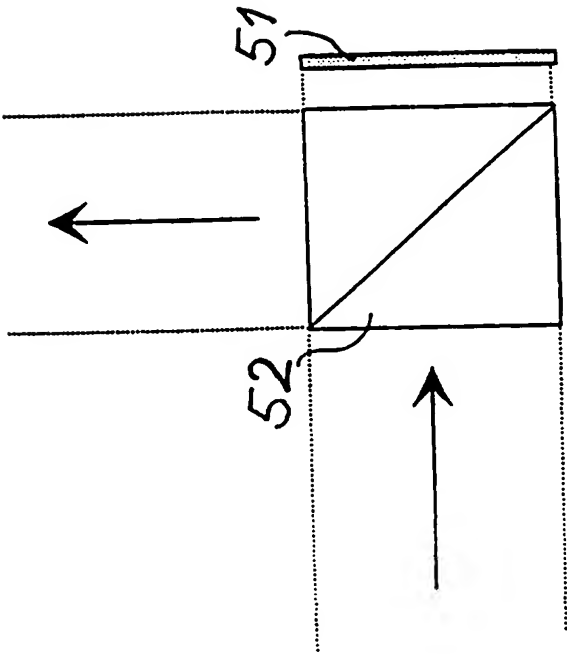47

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Fig. 3

(B)

(A)

Fig. 4

Fig. 5

Fig. 6

INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6   G02B27/52   G06E3/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 6   G02B   G06E

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	APPLIED OPTICS, NEW YORK, NY, US, vol. 27, no. 14, 15 July 1988, pages 2915-2921, XP002010327 LOHMANN A W ET AL: "ARRAY ILLUMINATOR BASED ON PHASE CONTRAST"	1,12, 34-36,39
A	see the whole document	37,40

X	GB,A,2 199 716 (MESSERSCHMITT BOELKOW BLOHM) 13 July 1988 cited in the application	1,12,34, 35,39, 40,42
A	see the whole document	36,37

P,X	EP,A,0 657 760 (TEXAS INSTRUMENTS INC) 14 June 1995 see the whole document	1,12,29, 34-40

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[X] Further documents are listed in the continuation of box C.   [X] Patent family members are listed in annex.

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
7 August 1996	14.08.96

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INTERNATIONAL SEARCH REPORT

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US,A,5 363 186 (COHN ROBERT W ET AL) 8 November 1994 see the whole document -----	1,34

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Patent document cited in search report	Publication date	Patent family member(s)		Publication date
GB-A-2199716	13-07-88	DE-C- FR-A-	3641541 2607915	09-06-88 10-06-88
EP-A-0657760	14-06-95	US-A-	5508841	16-04-96
US-A-5363186	08-11-94	NONE		